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Chapter 26

The Coral Reef Exhibit at Reef HQ Aquarium, Townsville, Australia: Technical operations and water quality

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ABSTRACT
Reef HQ Aquarium, previously named the Great Barrier Reef Aquarium, houses the world's largest living coral reef aquarium system, called the Coral Reef Exhibit (CRE). Over 20 years of CRE operation, water management has evolved significantly to improve the overall health of the tank. This chapter describes the present mode of technical operation of the CRE with a focus on water quality and compares with previous experiences. An increase in coral survival since current methods are in place indicates that a shift from occasional water exchanges using *a priori* ultra-clean oceanic water to regular exchanges with 'less pure' estuarine water has been largely beneficial to the CRE. Reduced mechanical filtration and increased general and localized flow have also contributed to a healthier system, which is very tolerant to large natural variations in some water quality parameters.

INTRODUCTION

The Coral Reef Exhibit (CRE) at Reef HQ Aquarium in Townsville, Australia, is a 2.8-million liter living coral reef mesocosm designed to replicate an inshore reef on land (Eager and Peterson, 1988). Built in 1987, and located in the coastal tropics in Townsville near the middle of the Great Barrier Reef (Figure 1), Reef HQ had several natural advantages to accomplish this, including a tropical climate, open access to sunlight, and ready coral availability. Nevertheless, building the largest living coral reef aquarium in the world included numerous technical challenges at the time, and, although advances in coral husbandry have been made around the world in terms of coral husbandry in the last two or three decades, challenges still remain 20 years later. Ongoing improvements in water quality and filtration methods, as well as altered collection and husbandry techniques, have led to vastly increased long-term survival rates for most coral species (reviewed in Chapter 9).

The objective of this chapter is to review the history of changes in CRE operations, and to provide detailed information about the "hardware" side of operations, including water supply, filtration, illumination, circulation and water quality. It also includes a brief summary of the practices that have been applied to CRE maintenance during the first 20 years (some no longer in use) in order to provide a background to current practices, a history of water quality parameters and the techniques in place to control these parameters, and a summary of what works best for the system.

TECHNICAL OPERATIONS IN THE CRE

The CRE is a semi-rectangular tank (35 meters length by 17 meters width and 4.5 meters depth) that holds over 2.5 million L of seawater

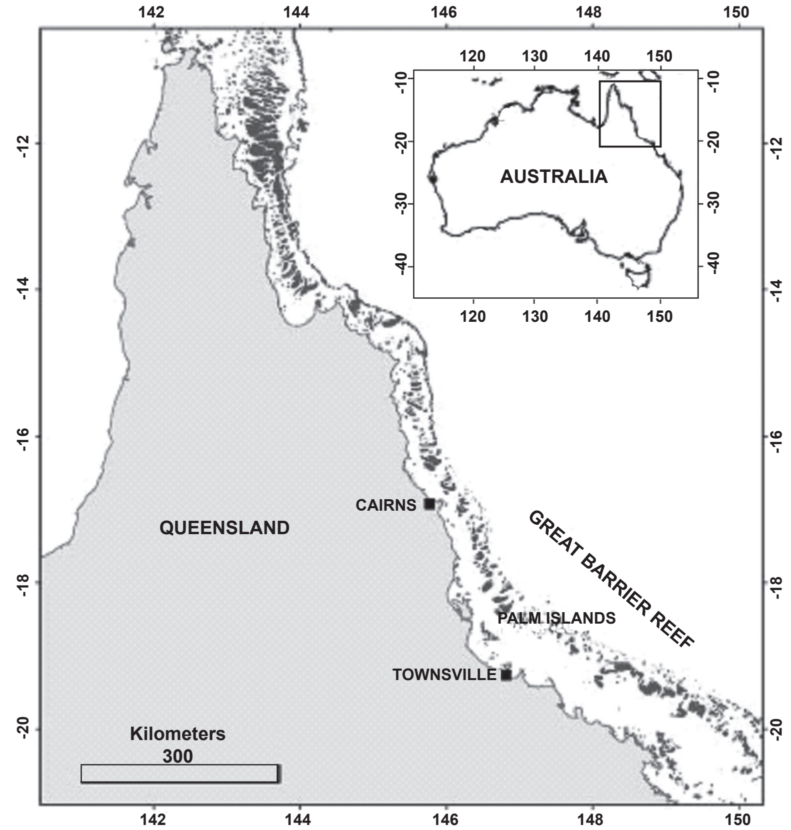

Figure 1: Map of the Great Barrier Reef and location of the Reef HQ Aquarium in Townsville in relation to the coast of Australia.

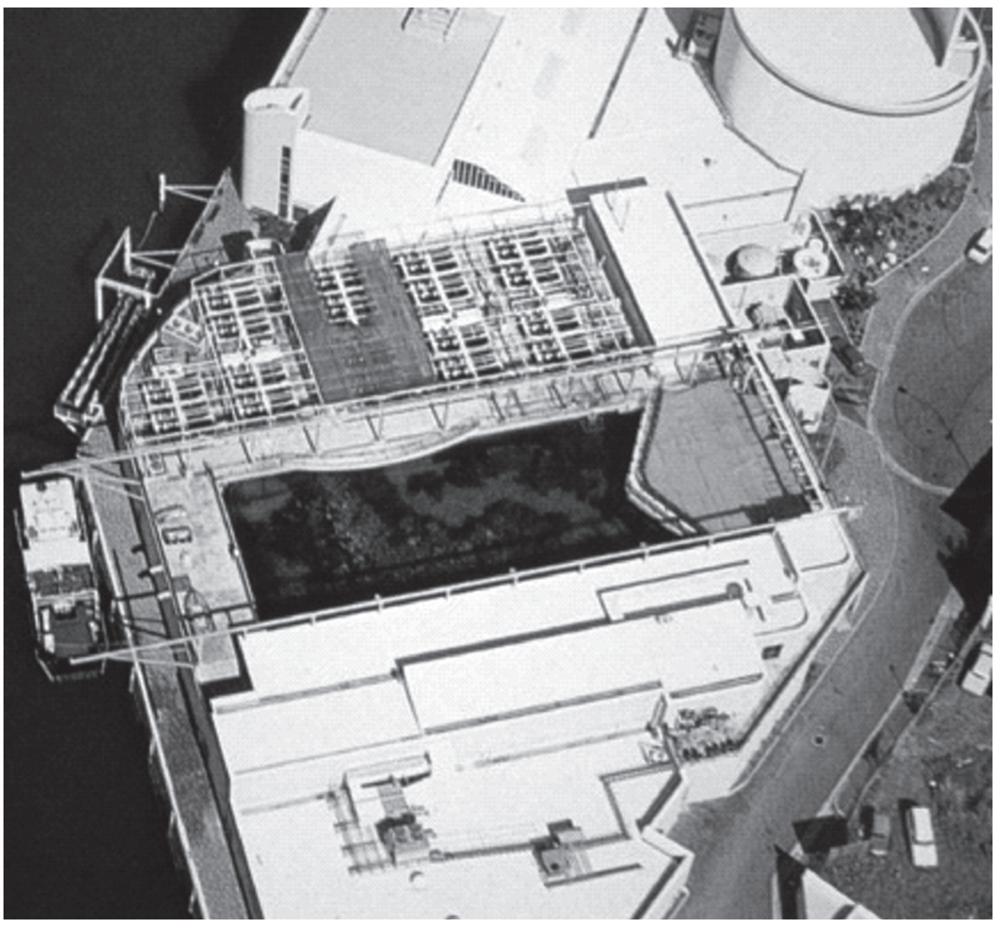

Figure 2: Photograph dating pre-2002 of the Coral Reef Exhibit showing its design and the surrounding Reef HQ Aquarium rooftop as seen from above. Note: the Algal Turf Farm – (square grids visible next to the tank at the top of the picture) is no longer in place.

and 700 tons of live rock and corals and a coarse carbonate sand substrate of varying depths (20 - 100 cm) (Figure 2). It is connected to a separate tank of approximately 700,000 L volume that serves as an intake, holding, and testing container for new seawater when both tanks are isolated, as well as a circulating and chilling vessel in summer when both tanks are in line. As a result, the CRE volume varies from 2.5 to 3.2 million L and is considered to be 2.8 million L on average when circulating.

The CRE is fully open to the elements at all times and exists in a climate marked by two main seasons: dry and cool to warm between May and September, and warmer to very hot between October and April. The rainy season usually spans from late December until the end of March, with an average yearly rainfall in Townsville of 500 mm. Finally, Townsville is located in a cyclone-susceptible region most likely to occur during the summer monsoon.

Over its 20 years of existence, operation and water treatment of the CRE can be divided into two stages: pre-2002, when tank exchange water was sourced from off-shore ocean waters, and post 2002 where estuarine water is used. These two periods will be referred to in this paper as the “Oceanic Water period” and the “Estuarine Water period” respectively, and correspond to significant changes in filtration methods. As a consequence of these changes, coral health and survival have also shown significant improvements in the later period, as discussed in Chapter 9.

THE OCEANIC WATER PERIOD (PRE-2002)

Water source and exchange

For the first 15 years (between 1987 and 2002), the CRE was a completely closed system, and new seawater for the exhibit was supplied exclusively by barge. The water was sourced offshore where water depth exceeds 20 m, near the mid-shelf Palm Islands Group. This approach was chosen to ensure clean water for the tank, as inshore waters surrounding Townsville were thought to carry too much sediment, nutrients, and possibly heavy metals and other toxins or contaminants from the nearby rail yards and shipping channel located directly across from the Aquarium.

A single barge load contained approximately 300,000 L, or around 1/10 of the total CRE system, and exchange only occurred at a maximum of one load per month, depending on season and budget limitations. The Oceanic Water period corresponds to a period of very low coral survival, discussed in later sections.

Water analysis

Before introduction into the CRE, samples of the seawater barged into Reef HQ were analyzed to ensure the seawater was within acceptable limits for inorganic nitrogen and salinity. Samples were also subjected to a visual test for clarity, and a smell test for volatile contaminants, such as oil. On one occasion, the delivered seawater was contaminated with diesel fuel and was rejected, and an additional small number of deliveries were rejected due to not meeting salinity or clarity specifications.

Filtration

During the Oceanic Water period, filtration was carried out by three large sand filters (20 µm grain size) of 2000 liters each, as well as by an Algal Turf Farm (ATF) (Adey and Loveland, 1981), located on the roof of the aquarium (visible in Figure 2, top center). The ATF consisted of 70 shallow PVC trays approximately 2 m in length and 1 m in width covered with a 1 mm screen mesh to serve as an algae substrate. The trays were exposed to sunlight plus additional overhead growing lamps that were operated at night and during cloudy periods. CRE water was circulated through attached pipes and poured onto the trays *via* 20 L tipping buckets that filled and then tipped at *ca.* 30-second intervals (depending on flow rate adjustments).

Algal masses (*Enteromorpha* spp.) growing on the mesh absorbed excess inorganic nutrients from the CRE water, and provided oxygen and stable pH levels. By manually removing the algae from the trays, these inorganic nutrients were removed from the CRE. However, this method required intensive labor and eventually became obsolete during the Estuarine Water period.

Water circulation

For the first 15 years, water movement was created partly by the return of the sand filters, and partly by a wave machine driven by compressed air (still in use today). The wave machine operates by compressing air inside four chambers blocked by a concrete slab on the top, by the tank wall or separating walls on 4 sides, and by the tank water at the bottom. The four chambers are spread over the entire width of the tank. At regular intervals, and after air is compressed, flaps inside the chambers

open to the atmosphere, rapidly releasing the compressed air, thereby sucking the tank water upwards. When the water level drops again by gravity, a wave is created and propagates over the entire length of the tank. The system allows for an offset in the compression frequency in each chamber, which can cause turbulence and interfere with water motion.

THE ESTUARINE WATER PERIOD (POST-2002)

Water source and exchange

A significant shift occurred during 2002 when the aquarium was closed to the public for almost five months to maintain and upgrade the facility. Based on the analysis of existing practices and resulting low coral survival, this period was also used as an important opportunity to modify CRE operations, starting with its water source and exchange. The driving forces behind these changes were the obvious low coral survival rates and the fact that calcium levels (~ 250 mg $Ca^{2+}.L^{-1}$, point readings available only) and inorganic nutrient levels were low.

Due to the major shipping and harbor facilities on the ocean side, a quickly-growing city and rail yard operations on the river side, and the highly turbid nature of Townsville's inshore reef waters, a continuous flow-through system was ruled out. Instead, following a major review of available and affordable water quality testing methods and a thorough risk analysis, a single-batch intake system was devised.

The process begins with isolation of the 700,000 L holding tank from the CRE, and dumping of the contained seawater into the higher-nutrient "Predator Tank" for water exchange in that system. Water is then pumped into the holding tank on the incoming tide from the tidal creek (Ross Creek) running directly alongside the aquarium. This "intake water" initially passes through a 20 µm sand filter (SM2000, Waterco, Australia) to remove larger particulates before being stored and recirculated in the holding tank, and is tested for potential toxins and out-of-range water quality parameters. If any of the testing standards are not met, the intake water is rejected; otherwise it is mixed with the CRE within 36-40 h after intake. This exchange is normally carried out at least once every two weeks, with some variation depending on rainfall, evaporation, nutrient levels, and staff/time available. As of 2007, rejection of batches has only occurred four times since intakes began in 2002.

Filtration

During the same time period as the change from oceanic water to estuarine water was occurring, CRE filtration philosophy shifted away from the Algal Turf Farm towards the implementation of large-scale protein skimmers. Following several water quality monitoring trials where sections of the ATF were turned off, it was determined that the ATF effects on CRE filtration were negligible, especially when compared to the CRE's internal algal mass productivity. The

Figure 3: Photograph of the open surface of the Coral Reef Exhibit showing some of the protective shadecloth system (on left) and the two protein skimmers (center).

ATF was considered obsolete and taken offline permanently from the CRE in late 2002, and replaced by a bank of nine protein skimmers. The sand filters were also taken off-line from the CRE in 2005 to increase plankton productivity within the tank and allow natural settlement of larval organisms coming in with the tidal creek water intakes.

After several modifications to the protein skimmer system, the entire bank was replaced by two industrial-sized protein skimmers in August 2005 (Figure 3) (IPS90, Ozone Technologies, New Zealand). Since then, these skimmers have been the sole artificial filtration system for the CRE. Each skimmer has its own ozone supply set at a standard rate of 5 $g.h^{-1}$ per skimmer, and an experiment is carried out to test the effect of one skimmer out of two fed by 10 $g.h^{-1}$, as long as internal CRE chlorine levels remain stable.

Water circulation

General water movement in the CRE is created by the wave machine (described previously) and three large pumps (30 to 70 $L.s^{-1}$ flow rates or 100 to 250 $m^3.h^{-1}$, see Appendix I), including one pump for the skimmers and two recirculation pumps with intake and outflow pipes at different sides of the tank. In 2002, after review of the CRE internal flow using measurements of red dye movement through the water column (Michalek-Wagner, unpubl. data), it was apparent that within-tank circulation was not sufficient for sustaining coral health and stimulating colony growth. In order to increase this internal circulation and to create more turbulent flow patterns, especially for ‘dead zones’ around the reef structure, a network of small submersible double-impeller aquaculture pumps (Brio 415V, AquaEco, Italy, referred to as circulators) was installed in 2003 in various locations throughout the tank. A more permanent network of 15 circulators was then deployed in 2005 at various depths and directed towards main reef areas, focusing on viewing windows. Each circulator creates a current of up to 0.2 - 0.4 $m.s^{-1}$ at least 3 m away from the impellors, depending on other current sources in the surroundings (i.e. outflow pipes).

MONITORING AND MAINTENANCE OF WATER QUALITY IN THE CRE

Figure 4 shows a 10-year time-series of basic water quality parameters routinely monitored in the CRE during both the Oceanic Water and the Estuarine Water periods (1997-2007), i.e. either side of the change in water supply. These figures illustrate the changes in various measurements following operational changes, and some seasonal variations can also be seen. Average water quality values in the Coral Reef Exhibit in 2007 and comparisons to optimal and/or natural water quality parameters are summarized in Appendix I. Information is also provided on the potential control mechanism available, where applicable.

Temperature

Temperature in the CRE varies greatly over the year with seasonal changes, from 20-22 ºC at the height of the australian winter (July) to over 32 ºC under normal uncontrolled conditions (Figure 4a). Daily natural variability due to daytime heating and nighttime cooling is between 0.5 and 1 °C from minimum to maximum, depending on time of year and weather conditions. Although it is not currently viable to control winter cooling of the tank, summer heating effects are reduced by either large mesh shade cloths that can be pulled above the tank during the day, and/or the aquarium building’s air conditioning coolant that is circulated through a secondary chiller coil inside the supplemental holding tank. This allows the temperature to be maintained at or below 29.5 ºC for most of the time in summer, although water temperatures can quickly rise above 30 ºC or greater during water intake operations when the CRE is isolated from the holding tank for up to 40 h.

pH

pH now varies from 7.9 to 8.2 (Figure 4a) and no direct controls are applied to the CRE, other than indirectly by maintaining the alkalinity at higher than natural levels (between 3.0 and 3.3 $mEq.L^{-1}$). Due to algal photosynthesis on sunny days, pH increases from the morning to the afternoon by approximately 0.1 to 0.2 units, with a typical pH of 8.05 at 08:00 hours and a pH of 8.15 at 16:30 hours.

Salinity

Salinity also varies largely throughout the year (Figure 4a) due to evaporation during the dry, sunny winter and high rainfall in summer. It is not regulated except when evaporation increases salinity above 37 at the end of winter and before the rain season starts – in which case tap water can be added to the tank – or under conditions

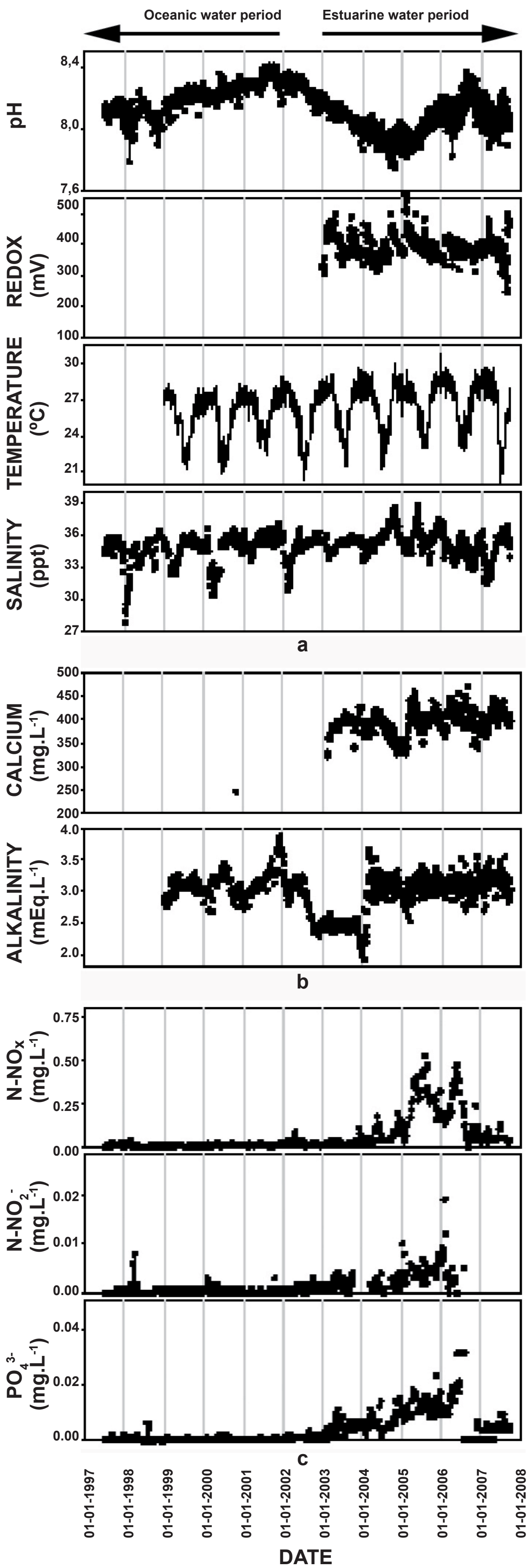

Figure 4: Time series of basic water quality parameters in the Coral Reef Exhibit over the decade of 1997-2007: a) pH, Redox potential, temperature and salinity; b) calcium and alkalinity; c) nitrate, nitrite and phosphorous.

of extraordinary rainfall events. In 1998, over 700 mm of rain fell within a 36-hour period and reduced the tank salinity from 34 to less than 28 ppt. No noticeable effects on the fish were observed, but detrimental effects on corals and other invertebrates were more difficult to assess, as corals were dying on a regular basis anyway at the time. Four *Acropora* spp. colonies died in the days immediately following the rain event (Suosaari, pers. com.), but comparisons with previous and following years showed no clear differences in colony mortality (based on the Coral Log kept at the time, as reviewed in later sections).

The risk of such an event recurring led to the installation of the reverse-osmosis system to mitigate the potential for massive coral death, in particular after coral survival increased drastically and risk therefore increased. However, this system is still not satisfactory to cope with similar events in the future, which are statistically very rare but could have dramatic consequences. The addition of several metric tons of salt was also tried after the 1998 event (and again in 2008), but the storage requirements of such a sheer amount of salt, in addition to the logistical difficulty of mixing such large quantities in a crisis situation, make this contingency plan unreliable.

Reduction-oxidation potential

Reduction-oxidation (redox) potential is only measured as an indicator, and is not used for decision-making because of the unreliability of redox measurements. Redox potential varies from 300-500 mV in the CRE, with a typical daily measurement of 380-400 mV (Figure 4a).

Dissolved Oxygen

Dissolved Oxygen (DO) is not controlled and is allowed to fluctuate naturally within the CRE. Levels are generally very predictable and stable, reading approximately 90 % in the morning and increasing to over 100 % by the late afternoon, with daily variations in the order of +10-20 % due to photosynthesis and depending on weather conditions. In an emergency, DO can be increased by opening intake valves to the ambient air thereby creating suction from the Venturi effect, or by using an emergency bubbler system that is currently under trial in the smaller 750,000 L 'Predator Tank'. However, these controls have not been tested under a crisis situation, and are considered solely to be minor backup systems.

Calcium

Calcium levels of intake water from the tidal Ross Creek measure between 350 and 370 mg $Ca^{2+}.L^{-1}$, which drops the calcium concentration in the CRE by dilution following water exchange (Figure 4b). To attain the desired concentrations of 420 mg $Ca^{2+}.L^{-1}$, calcium chloride ($CaCl_2$) is used to supplement the CRE calcium levels. Bags weighing 25 kg are attached to a hook and rope-pulley, punctured in several places, lowered into the tank in a high current area near an outflow pipe, and left overnight to dilute. The standard addition rate equals about 6 metric tons per year of food grade calcium chloride flakes (averaging out to 1 bag every 1.5 d).

Alkalinity

Alkalinity is maintained at 3.0 to 3.5 $mEq.L^{-1}$ (Figure 4b) above the natural seawater concentration of 2.6 $mEq.L^{-1}$ in order to increase buffering capacity and encourage coral calcification. Food-grade sodium bicarbonate ($NaHCO_3$) is added to one of the CRE refugia, small shallow reservoirs that are inline with the CRE with a low but constant water circulation. 50 kg at a time is poured into a refugium once or twice per week, depending on daily water quality test results, and allowed to slowly dissolve overnight. The current addition rate is approximately 3.5 metric tons per year.

Changing the Na:Cl ratio through calcium chloride and sodium bicarbonate additions is not a serious concern because the CRE has a relatively high renewal rate with large volumes of natural seawater mixed weekly or fortnightly. In fact, this dilution effect can become counter-productive to chemical additions and a drop in calcium and alkalinity levels is measurable (drop of approximately 25 mg $Mg^{2+}.L^{-1}$ and 0.2 $mEq.L^{-1}$ per intake, respectively) on the day following a new creek water intake into the CRE.

Magnesium

Magnesium is not routinely measured but occasional tests show magnesium concentrations holding stable between 1150 and 1200 mg $Mg^{2+}.L^{-1}$. Magnesium levels are not actively controlled; however, the circulators used to create currents are each equipped with magnesium anodes to avoid corrosion. The slow dissolution of these anodes equates to approximately 350 kg of magnesium per year added to the tank.

Chlorine

Chlorine is measured via a DPD test, and is used as an approximate indication of all residual oxidants in the tank. Typical residual chlorine is around 0.03 $mg.L^{-1}$, however it can increase if the ozone input into the protein skimmers increases. As a guideline, ozone input is reduced if chlorine levels increase to 0.06 $mg.L^{-1}$ or greater.

Nutrients

Levels of dissolved inorganic and organic nutrients in the CRE are measured using a Lachat Quick Chem 8000 flow injection analyzer (FIA). The principle of an FIA is to inject the sample of water to be analyzed into a flowing stream of carrier, inject the reagents that cause a color reaction, and then measure the intensity of the color peak with an optical detector. Dissolved inorganic nitrogen compounds and orthophosphates are determined using standard protocols as outlined in the Lachat manual. Dissolved and particulate organic nutrient samples (Nitrogen and Phosphorous) are first digested with alkaline potassium persulfate and autoclaved for 30 minutes at 15 PSI (121 °C), then determined as for the inorganic samples.

Inorganic nutrient levels in the CRE (Figure 6) are greater than those of natural clear reef waters but still comparable to those encountered on nearby inshore reefs (Furnas *et al*., 1995). CRE nutrient levels are maintained by natural internal biofiltration, vacuuming of excess macroalgae, and by protein skimmers. In addition, tidal creek water intake nutrient levels are generally lower than the CRE (except during heavy rains), helping to flush the system during water exchanges. Finer-scale fluctuations can occur with increases in rainfall and/or reduced water exchange, but the overall nutrient levels have now stabilized at around 0.1-0.2 mg NO_3^--$N.L^{-1}$ and 0.01 mg PO_4^{3-}-$P.L^{-1}$ (Figure 4c).

Light

The CRE is exposed to natural light conditions, which is an average of 320 d of sunshine a year for the Townsville region. Coral colonies that are located near the tank walls are partially shaded from the sunlight by these. In summer, when illumination and temperature are high, large shadecloths that cover the entire area of the CRE can be pulled down to reduce UV exposure and illumination. These are pulled down 2 or 3 days a week for about 2 or 3 months at the hottest time of the year. Total daily illumination is in the order of 10 to 15 $\mu E.m^{-2}.d^{-1}$ with maximum illumination varying from 300 to 700 $\mu E.m^{-2}.s^{-1}$, depending on location in the tank and time of the year (Appendix I).

In comparison to a typical profile of summer light levels measured at a nearby inshore reef at the same depth, the CRE light level at 4 m depth is equal to approximately half of the natural illumination in the field in terms of peak levels (Figure 5) and half to a third in terms of daily illumination.

DISCUSSION

Operational changes and improvements in water quality have advanced considerably in the CRE since opening in 1987. The overall biological health of the system (discussed further in Chapter 9), also progressed following the start of the Estuarine Water period, partly due to normalization of calcium concentrations and better flow conditions from installation of the circulator pumps. The authors strongly believe that these changes were the most critical to improving coral survival (see Chapter 9).

Creek water intakes and large water exchanges also provided an external source of plankton; this, combined with the greatly reduced filtration of internal plankton populations, potentially increased food availability in the system, benefiting corals as well as filter feeding organisms. Comparative plankton counts throughout the time periods of operational changes found an increased number and diversity of plankton species, as well as the newer presence of larval organisms and larval fish stages (Anthony, unpubl. data). These results indicate that the reduced filtration allows greater time for potential larval development and settlement.

The only detrimental effect observed as a result of the CRE operational changes is occasional increased turbidity (especially following water exchange), which translates to reduced visibility for visitors to the Aquarium. Water exchange planning for after-hours mixing and improved ozone supply to new protein skimmers have helped to mitigate this problem. Although increased ozone dosages could improve visitor experience, the authors feel that some amount of suspended matter is beneficial to coral health in general, and a perfectly clear water body is not as desirable as the ability to maintain as complete an ecosystem as possible in the CRE.

CONCLUSIONS

Based on over 20 years of data from CRE operations history the authors conclude the following:

1. A shift from occasional water exchanges using *a priori* ultra-clean oceanic water to regular exchanges with 'less pure' estuarine water has been largely beneficial to the CRE.

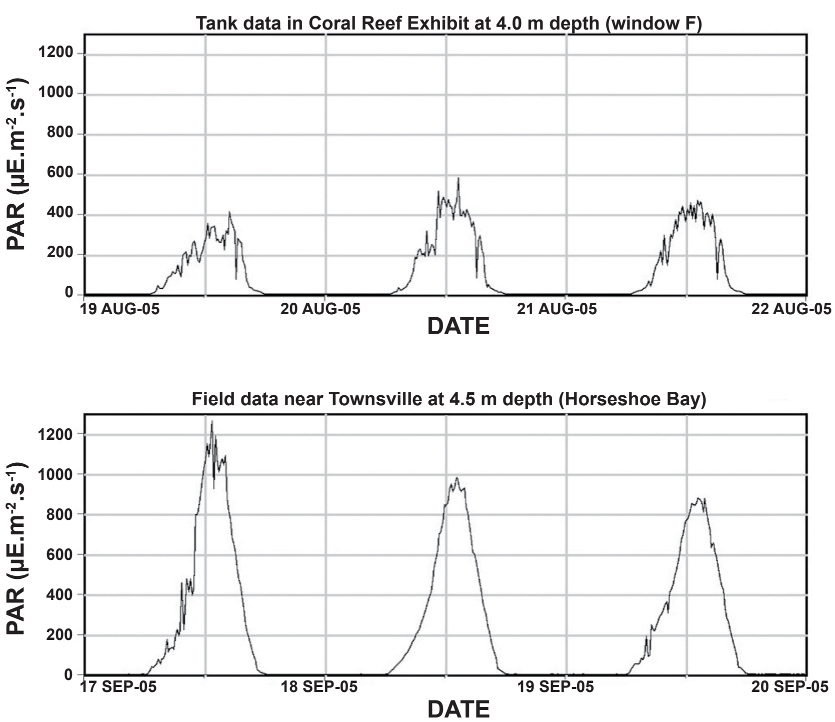

Figure 5: Typical profiles of daily late summer light levels in the Coral Reef Exhibit and a comparative nearby natural inshore reef.

2. Reduced mechanical filtration, such as sand filters, in large-scale systems such as the CRE can improve overall tank health by avoiding 'overstripping' the water column of particulates and encouraging plankton production, greater food availability, and larval settlement.
3. Though overall stability within acceptable ranges of water quality parameters is most important, the CRE undergoes large short-term variations in some water quality parameters, such as salinity and temperature, without significant adverse effects.
4. Although many improvements have already taken place, CRE water quality conditions could be improved further by increased water flow in local areas. The addition of more circulator pumps throughout the tank is technically feasible, in particular to target specific reef areas with stronger flow, but it is difficult to keep such local mechanisms both relatively cheap and still invisible to outside viewing, which is what Reef HQ is trying to achieve when recreating a whole reef mesocosm.

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APPENDIX I: Aquarium Passport of the coral reef exhibit at Reef HQ Aquarium, Towmsville, Australia.

Tank name	Coral Reef Exhibit
Location	Reef HQ Aquarium at the Great Barrier Reef Marine Park Authority (Townsville, Australia)
Opening date	June 1987

INFRASTRUCTURE / PHYSICAL DESCRIPTION

Volume	2.5 + ~0.7 million liters on line in holding tank - Average volume: 2.8 million liters
Surface area	~35 m x 17 m approximately rectangular = ~580 m^2
Depth	4.5 m everywhere, corals from 1 to 4.5 m

LIGHT CONDITIONS

Day	Natural light only with some shading from walls. Tank fully open to the sky
Night	Natural moonlight with some shading from walls
Hours of illumination	Direct sunlight, depending on location: - 3 to 6 h in winter - 5 to 8 h in summer Indirect sunlight: 10 to 14 h depending on season

Daily max PAR	0.5 to 1 m depth	2.5 m depth	4.0 m depth
($\mu E.m^{-2}.s^{-1}$) Winter	900 to 1,800	NA	300 to 400
($\mu E.m^{-2}.s^{-1}$) Summer	1,500 to 2,000+	NA	500 to 700
Total daily integrated daylight [1] ($\mu E.m^{-2}.d^{-1}$)	0.5 to 1 m depth	2.5 m depth	4.0 m depth
	23 to 30 depending on location and season	NA	5 to 15 depending on location and season

FILTRATION (external)

Protein skimmers	2 x IPS 90 from Ozone Technologies, 2 m^3 each, 2 x 90 $m^3.h^{-1}$ = 180 $m^3.h^{-1}$r in total, ~16 h turn around of tank through skimmers
Ozone injection	Application rate: 0.05 $mg.L^{-1}$ at each passage in skimmer, contact time of 1.5 min, 0.003 $mg.L^{-1}.h^{-1}$ on average
Sand filters	Sand filters are not used but there is a stand-by capacity of 3 x 2000 L sand filters filled with zeolite or 300 $m^3.h^{-1}$ in total (Waterco SM2000)
Vacuum by divers	~1 $h.d^{-1}$ on average removing algae and fine detritus

FILTRATION (internal)

Live-rocks	700 tons of carbonate rock (dolomite, not aragonite), not including corals skeletons added to tank over ~17 yrs of collection
Substrate	~300 tons of sand bed initially added to tank (unconfirmed number), 10 to 50 cm thick left in 2007, total living sand area ~ 300 m^2
Fauna	~ 20 *Diadema* spp. sea urchins +other urchin species (10-15 individuals), ~100 sea cucumbers [2] (unconfirmed number), seastars [3], brittle stars and feather stars (at least 20 of the latter), hermit crabs (unknown number), non-corallivorous snails (unknown number), *Trochus* > 200, *Strombus*, and spider shells. Refer to chapter 9 for fish list and fish count estimates

WATER MOVEMENT / CIRCULATION

External pumps	2 laminar flow outlets at ~ 100 $m^3.h^{-1}$ and ~200 $m^3.h^{-1}$ respectively
Submerged pumps	15 "circulator pumps"(Aqua Eco Brio 415 V 1.2 kW) creating currents over ~ 4 m range, with a flow of ~30 $m^3.h^{-1}$ each or 450 $m^3.h^{-1}$ in total
Wave machine	~ 30 cm amplitude pneumatic wave, period ~ 9 sec, creating orbital circulation throughout water column down to bottom

APPENDIX I (continued): Aquarium Passport of the coral reef exhibit at Reef HQ Aquarium, Towmsville, Australia.

Total flow	~ 500 $m^3.h^{-1}$ of which 67 % is unfiltered (without counting submerged pumps, guarantied flow) ~1000 $m^3.h^{-1}$ of which 82 % is unfiltered (with counting submerged pumps, estimated flow)
Flow in bottom 1 m	230 $m^3.h^{-1}$ (estimated)
Turn around rate [4]	~5 h (without counting submerged pumps, guarantied), 2 h (including submerged pumps, estimated)
Filtration flow	180 $m^3.h^{-1}$ (see external filtration above), including surface turbulence from protein skimmers return above surface
WATER CHANGES	
Type of system	Closed with large intakes of ocean water on a fortnightly basis under controlled conditions
Source of “new” salt-water	“new saltwater” = water from Ross Creek is pumped in tidal estuary of Ross Creek at flooding tide (hence water is largely ocean water) every fortnight on average (frequency depends on season) at ~ 550 m^3 each time. Water is quarantined, tested over 36 h, and mixed into tank at once (*ca.* 6 h for new water to get into the tank)
Characteristics of “new” saltwater	Calcium: 370 mg $Ca^{2+}.L^{-1}$ Magnesium: 1250 mg $Mg^{2+}.L^{-1}$ Salinity: 32 to 38 ppt Alkalinity : 2.5 $mEq.L^{-1}$ Temperature: 21-30 ºC pH: 8.1 Nutrients Nitrate: 0.01-0.14 mg NO_3^--N $.L^{-1}$ Nitrite: 0.001-0.014 mg NO_2^--$N.L^{-1}$ Phospate: 0.003-0.015 mg PO_4^{3-}-$P.L^{-1}$
Rate of water replacement	700 % per year
	FEEDING REGIME
Dead food	~ 500 $g.d^{-1}$ of aquaculture pellets in varying sizes (1 mm – 4 mm), ~ 200 g of frozen white bait or shrimp
Live food	None added currently - natural plankton supplies from *in-situ* reproduction and Creekwater intakes
	STOCKING
Origin	Central Great Barrier Reef region only, collected in the wild (corals) or bought from wholesaler (other invertebrates and fish)
Diversity	<u>Corals</u>: 143 hard coral species; 27 soft species; Estimated >1000 colonies (no recent count though) <u>Fish</u>: 167 species (last updated in 2006); No formal count, estimated > 5000 <u>Invertebrates</u>: See “fauna” in Internal filtration section
	CORAL STOCK MANAGEMENT
Data base	Corals tagged, Excel file record with date into tank, species, and date found dead (if at all) (from 1996 till 2005)
Health indicators	Approximate monthly photos of specific colonies
Quarantine	None for corals, corals directly introduced to tank after collection, generally none for fish purchased from reputable supplier

APPENDIX I (continued): Aquarium Passport of the coral reef exhibit at Reef HQ Aquarium, Towmsville, Australia.

WATER QUALITY (average based on 2007 data)

Parameter	CRE (2007)	Desired level	Controlled?
Salinity	32 – 38 (uncontrolled natural variations)	35	partially against high salinity through freshwater addition
Temperature (ºC)	20 to 30 °C with natural daily variations of ~1 °C	22 - 28	Yes against high temperatures. None against low temperatures
pH	7.9 - 8.2	8.2	Partially via alkalinity control
Dissolved Oxygen (%)	85 - 115	90-110	No (but possible if required)
Redox Potential (mV referenced to standard hydrogen electrode)	300 - 500	400 - 450	Partially via ozone input
Nutrients:			
Inorganic Phosphate (mg PO_4^{3-}-P.L^{-1})	0.01 - 0.03	NA	
Inorganic Nitrogen:			Water intakes
Nitrate (mg NO_x-N.L^{-1})	0.1 - 0.5	NA	Vacuuming of Macroalgae,
Nitrite (mg NO_2^--N.L^{-1})	0.001 - 0.01	NA	Natural biofiltration
Dissolved Organic Phosphate (equivalent mg PO_4^{3-}-P.L^{-1})	0 - 0.02	NA	Protein skimmers Ozone input
Dissolved Organic Nitrogen (equivalent mg NO_3^--N.L^{-1})	0.05 - 0.4	NA	

CHEMICAL ADDITIONS

Parameter	CRE (2007)	Desired level	Controlled?
Calcium (mg Ca^{2+}.L^{-1})	400 - 420	420 - 430	Yes: ~5 tons per year of calcium chloride (food grade): 25kg bag dissolved directly in tank in mesh bag suspended in current
Alkalinity (mEq.L^{-1})	2.9 – 3.4	3.0 - 3.5	Yes: ~ 3.5 tons of sodium bicarbonate (food grade) added per year: 25 kg bag added to refugium on line with the tank
Magnesium (mg Mg^{2+}.L-^{1})	1150 and 1200	1200	Addition via magnesium anodes for circulators: ~350 kg per year

1 Calculated from continuous record at 4 meters depth, integrated between 6 am and 6 pm, and averaged over many months of data at several locations in the tank.

2 Sea cucumber species include: *Bohadschia graeffei, Holothuria axiologa, Holothuria leucospilota, Stichopus chloronotus, Stichopus variegatus, Thelenota ananas, Pseudocolochirus violaceus*

3 Sea star species include: *Protoreaster nodosus, Choriaster granulatus, Nardoa novaecaledoniae, Linckia laevigata* (blue and brown morphs)

4 Time required to move every water particle at least once through the circulation and filtration systems